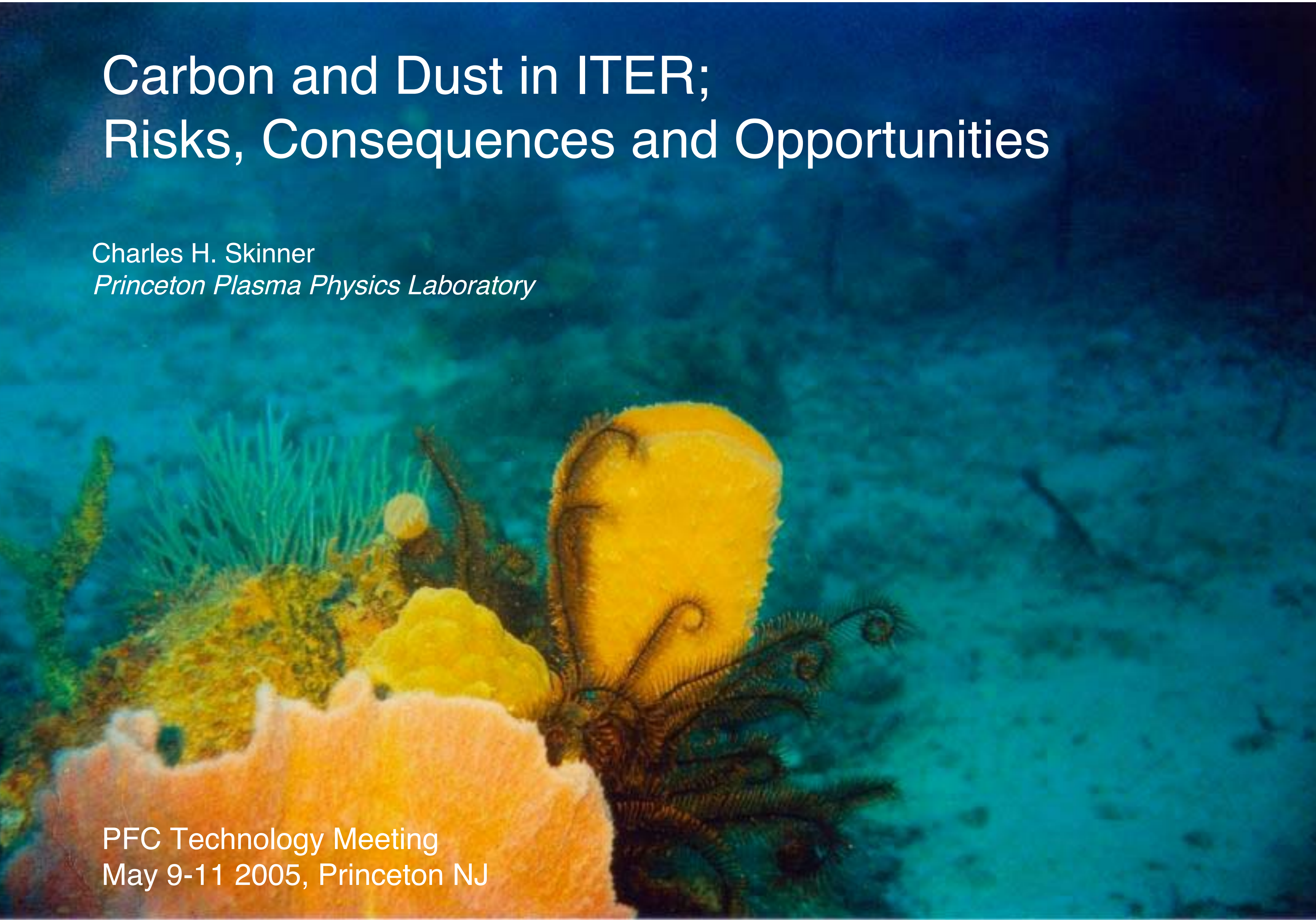


Carbon and Dust in ITER; Risks, Consequences and Opportunities

Charles H. Skinner
Princeton Plasma Physics Laboratory

PFC Technology Meeting
May 9-11 2005, Princeton NJ

Motivation:

- ITER is an Experiment
  - success is not guaranteed.
- Fusion Energy Research can be seen as a risk management project.

  Ongoing R&D can:
  - better quantify risks,
  - discover unforeseen risks, and
  - validate innovative solutions that minimize risks.
- Risk management issues are common in space exploration, investment, insurance, and new product development e.g. drugs, software….
- Worthwhile looking at experience and lessons learned in other fields.

http://www.nasa.gov

Brookhaven High Flux Beam Reactor once the premier source for neutron science, is undergoing decommissioning

e.g. "Programmatic Risk Analysis for Critical Engineering Systems under Tight Resource Constraints", R. L. Dillon, et al., Operations Research 51 (2003) 354.

ITER plasma facing materials:

Brief History:

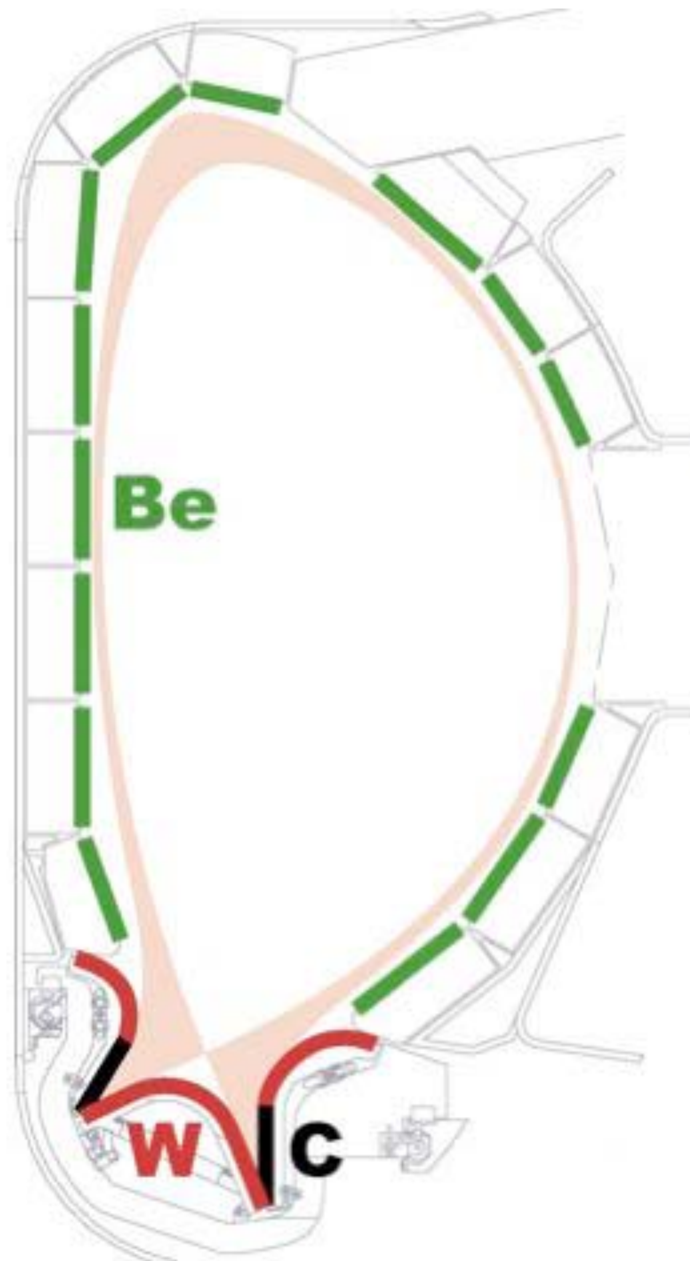
- 1978 PLT switch from W to C limiters enables first thermonuclear temperatures.
- 1988: Codeposition discovered on JET & TFTR
  - recognized as problem for T inventory.
- Be tested in ISX-B, then on JET wall + divertor to mitigate codeposition and getter oxygen.
- 1990 JET Be divertor melted - back to carbon for divertor
- Early 1990's: Be chosen for ITER wall, W for ITER dome & baffle and minimal C for divertor strike points to minimize codeposition and erosion.

Since then:

- Heavy T retention on TFTR/JET
- Cross field transport, ELMs
- Be/W alloys (PISCES) …

Present ITER PFC strategy:

- Use CFC in divertor for H/D operation,
- "Assess" H-isotope retention and melt layer loss for W.
- Decide on W or C divertor for DT operations



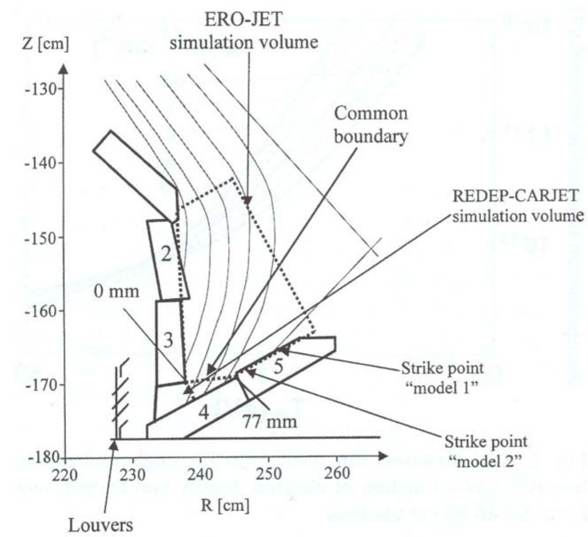
What is the potential impact of the tritium removal problem?

- Tritium inventory is a major safety factor and will be heavily scrutinized by regulatory authorities in licensing process.
- Public very sensitive to tritium issues.
- Cost of unforeseen delays ≈ > $1 million / day.
- At stake is not just the success of ITER, but the public credibility of fusion energy if ITER spends too long as PWI experiment.

Brookhaven High Flux Beam Reactor Area now cleared of experimental equipment

Tritium retention:
How well is the underlying physics understood?

- State-of-art modeling underestimates JET retention x40
- Model cannot reproduce detached plasmas on DIII-D (but has been successfully benchmarked in attached plasmas (Whyte)).
  - Major uncertainty is in chemical erosion yield
- Retention could be lower if:
  - Be layer impedes chemical sputtering (Doerner)
  - Chemical sputtering flux dependent (Roth)
- Retention could be higher if:
  - Wall is deposition area (Kukushkin)
  - Significant C erosion by ELMS
- Additional uncertainties from mixed materials.



JET MkIIA inner divertor geometry and calculation setup.

Brooks et al., J, Nucl. Mater 313-316 (2003) 424

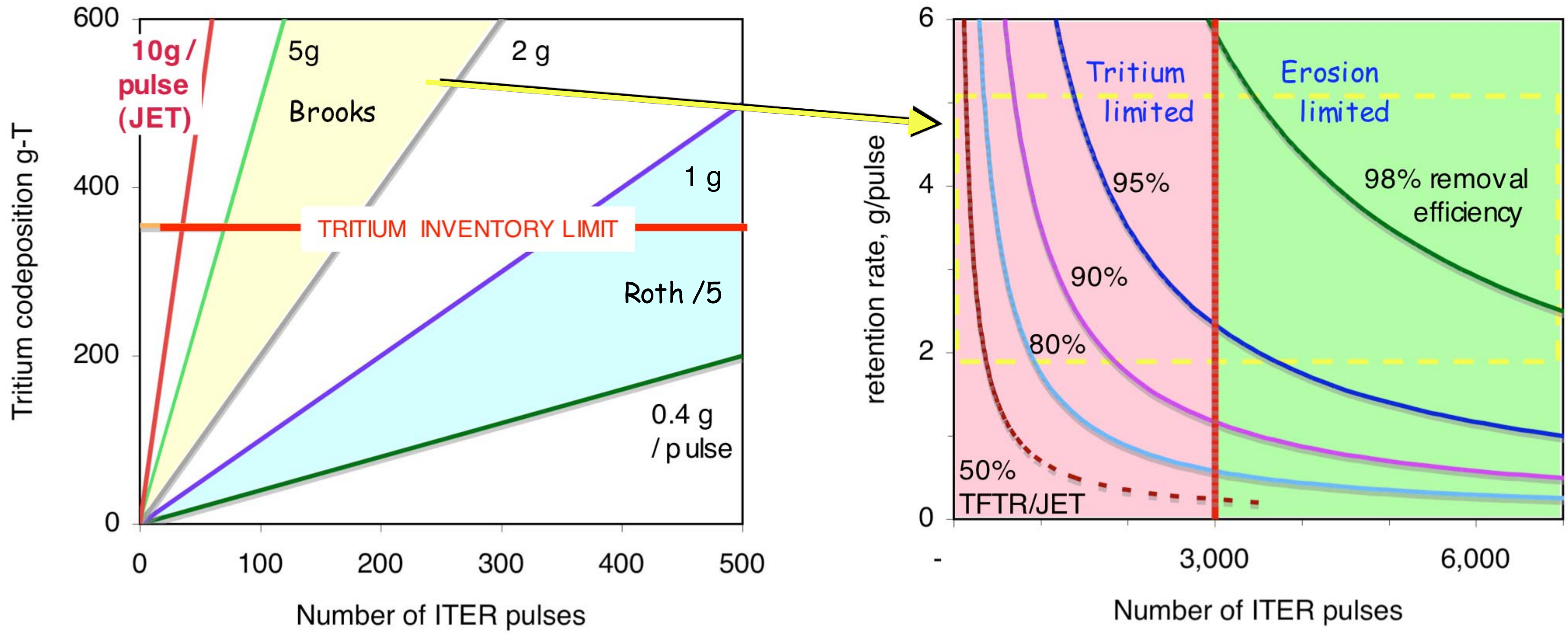
- Coupled REDEP and ERO-JET impurity transport calculations for sputtered wall/divertor carbon.
- MolDyn molecular dynamics calculations of carbon/hydrocarbon particle reflection at hydrogen-saturated carbon surfaces.
- ADAS full collisional radiative carbon ion recombination rate coefficients.

BOTTOM LINE: ITER should be able to cope with worst credible level of tritium retention.

ITER retention could be 100 g / day in 50 μm codeposit

Number of ITER pulses before tritium inventory limit is reached

Divertor lifetime vs. residual tritium



Tritium remaining after hypothetical removal can also stop operations at 350 g T limit.
Divertor exchange may be only way to remove it - IF it is on divertor.

To enable confidence in plasma operational schedule with carbon PFCs:

= capability to remove >90% tritium, up to 100 g and restore wall conditions in a

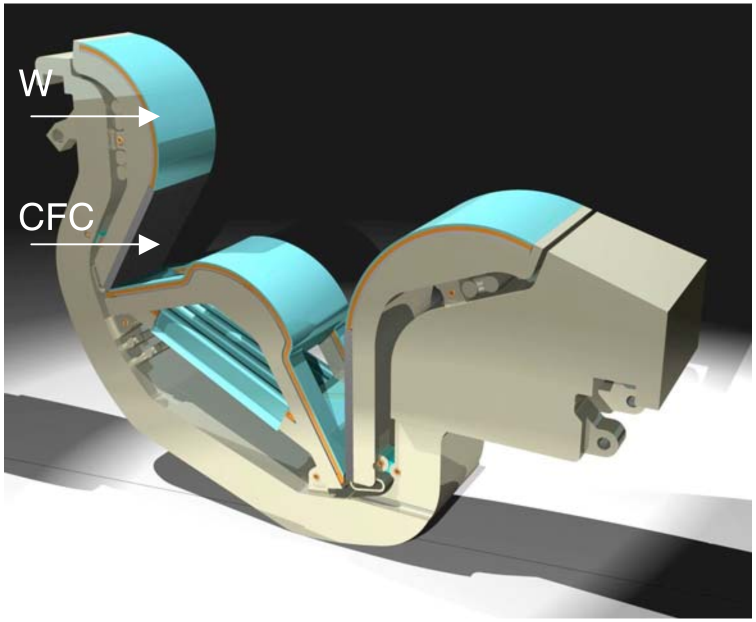
What technology is needed to resolve the problem?

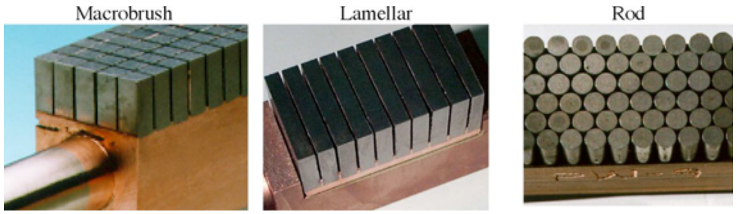
Tritium removal - potential options

1) Remove whole codeposit by:
   - oxidation (maybe aided by RF) ?
   - ablation with pulsed energy (laser or flashlamp) ?
2) Release T by breaking C:T chemical bond:
   - Isotope exchange ?
   - Heating to high temperatures e.g. by laser ?
   - or … ?
3) Constraints:
   - 6.1 Tessla field at inner divertor
   - 10,000 Gy/hr gamma field from activation, 3 h after shutdown, after 20 years DT ops.
   - Access difficult, especially to hidden areas location of tritium uncertain (under divertor dome, in flakes, bulk of CFC tiles.…)

T removal reviewed in Physica Scripta T111, 92-97, 2004.

ITER divertor cassette





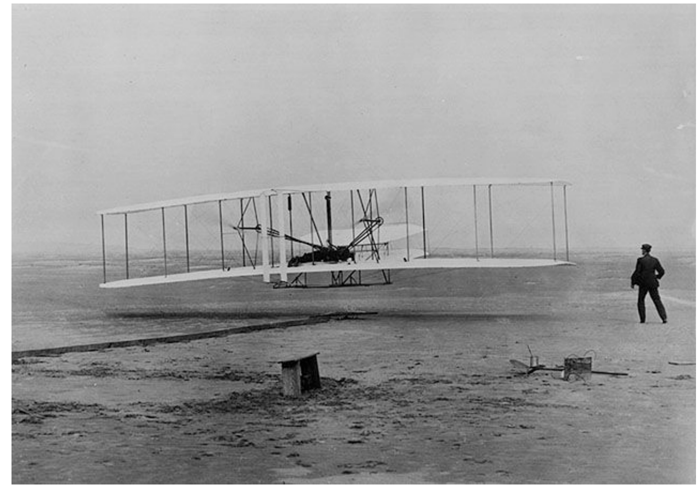
Castellated structures for W and CFC.
140 m^2 of gaps, 1 μm layer > 35 g-T !!!

Experiments to date immature, insufficient and underfunded.

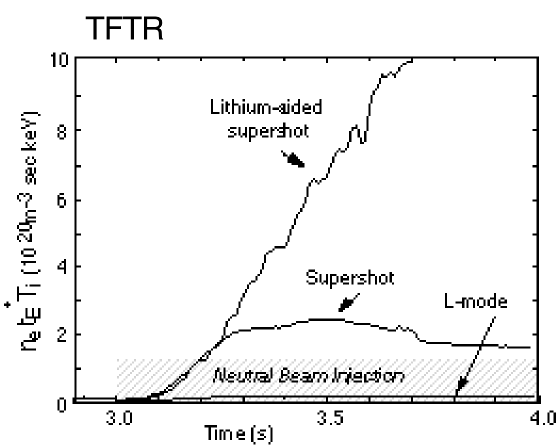
Are tokamak tests really necessary ?

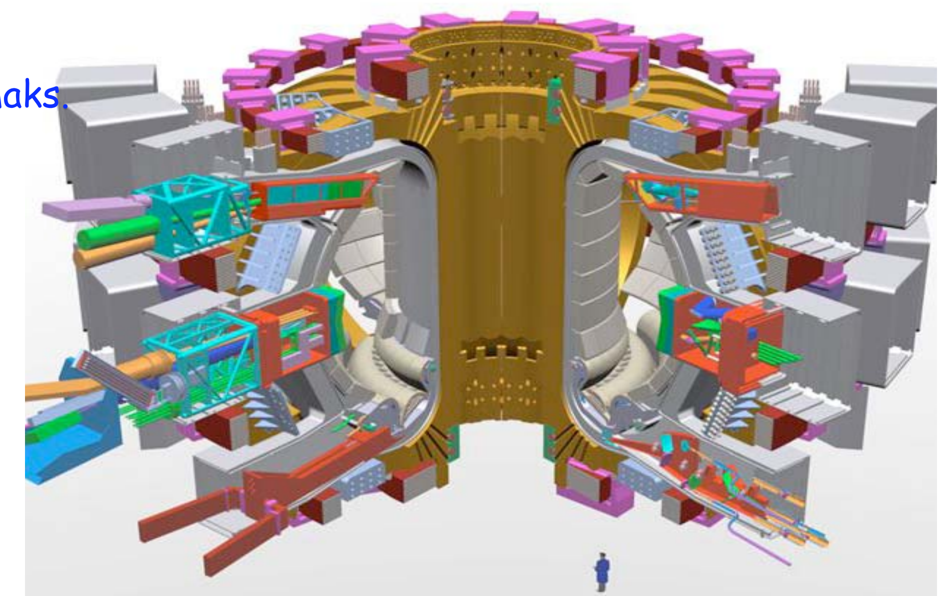
"If you are looking for perfect safety, you will do well to sit on a fence and watch the birds; but if you really wish to learn, you must mount a machine and become acquainted with its tricks by actual trial."

- Wilbur Wright, on learning to ride a flying machine



1. REABSORPTION ?
   The tritium removal rate of HeO GDC in TFTR was 20 times less than laboratory measurements.
2. WALL CONDITIONS:
   how long to restore high performance plasmas ?
3. TILE SURFACE? conditioned inside tokamak
4. CREDIBILITY? if too risky in present tokamaks.





PRESENT STATUS OF TRITIUM RETENTION AND REMOVAL:

1. No predictive understanding of tritium retention.
2. Tokamak tests rare and 10^4 short of removal rate required for ITER.
3. Development path from laboratory tests to ITER not specified.
4. Implications for ITER wall conditioning not explored.
5. Implications for ITER schedule of plasma operations not explored.
6. Implications for ITER tokamak exhaust processing system not explored
   - (Tokamak Exhaust Processing is US responsibility).
7. Diagnostics to measure deposition in DD phase not part of ITER diagnostic requirements.
8. Funding low or non-exisistent (diverted to fabricating major items of equipment ?)
   - golden opportunity to test laser detritiation on JET not funded by US.
9. Compare 14 talks on ELMs at PSI-16 to just 2 on tritium removal !
10. Risks unacknowledged - whose problem is it - management, physicists or engineers ?

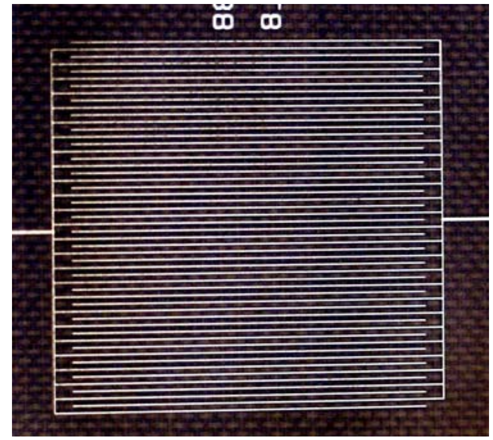
$\times 10^4$ scale-up required T removal rate - higher than any other ITER parameter **+** Lower R&D effort than any other area **=** HIGH RISK

- Risks of Carbon
- Risks of Dust
  - Lab results on novel electrostatic dust detector
  - Risks to ITER operations & goals
- Opportunities for US
  - How did we get here ?
  - What can we do about it ?

Novel electrostatic surface dust detector for remote surfaces

Principle:

- A fine grid of interlocking traces is biased with 30-50 v DC.
- Grid spacing down to 25 μm
- Impinging dust produces a short circuit and current pulse that vaporises the dust.
- A signal is generated by the return current and recorded with standard nuclear counting electronics
- Laboratory tests confirmed sensitivity in air and vacuum to test particles mechanically scraped from CFC tile



Rev. Sci. Instrum. **75,** 370 (2004).

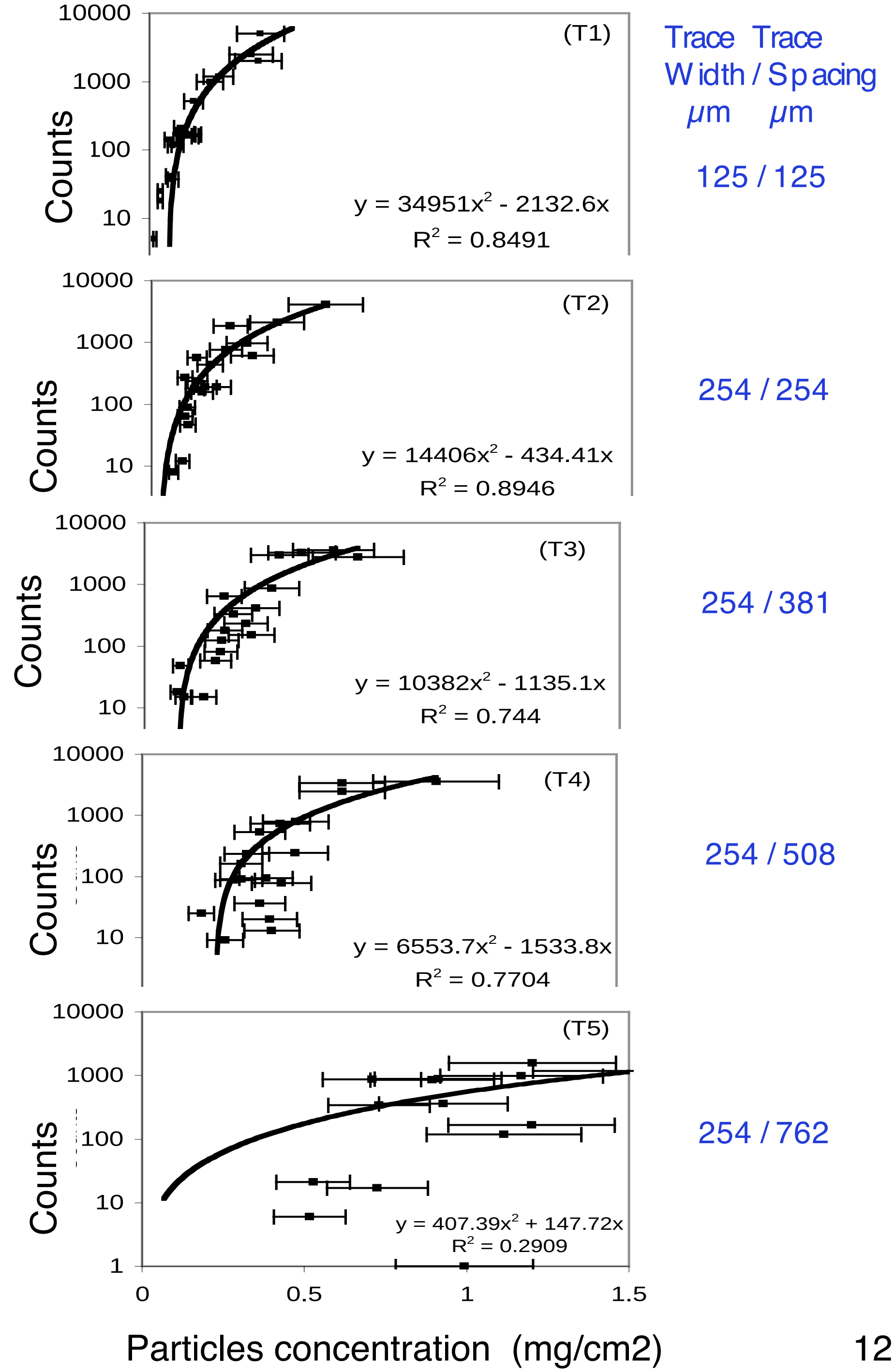
Recorded counts related to amount of particles:

Deliver preweighed amount of particles to grid in N_2 stream and record counts.

Particle delivery efficiency measured separately. Horizontal bars represent variability in particle deposition.

Correlation between recorded counts and particle concentration (mg/cm^2), especially at fine grid spacings (although operating principle is electrostatic not gravimetric).

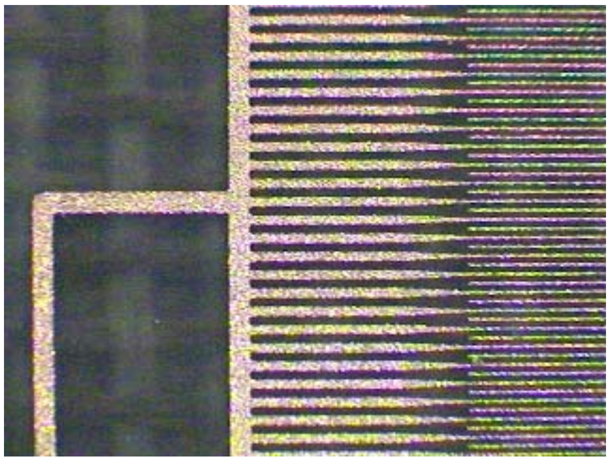
Data fit to 2nd order polynomial



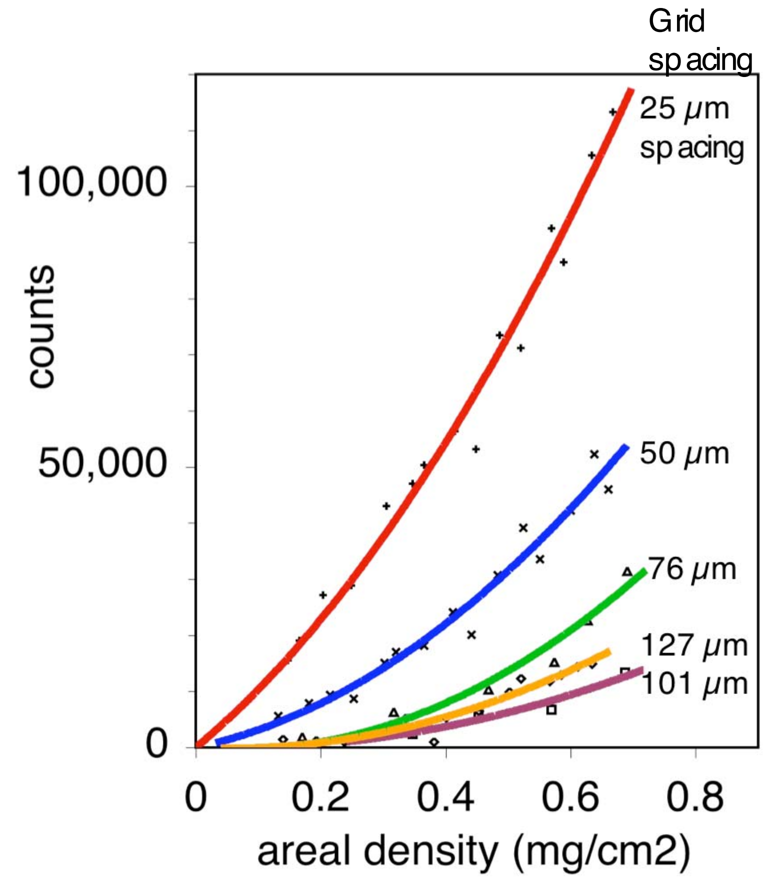
Aaron Bader, NUF fellow

Sensitivity increased ~ x 30 with finer grids

Close up of edge of grid with 25 μm traces



100 μm dia. of human hair



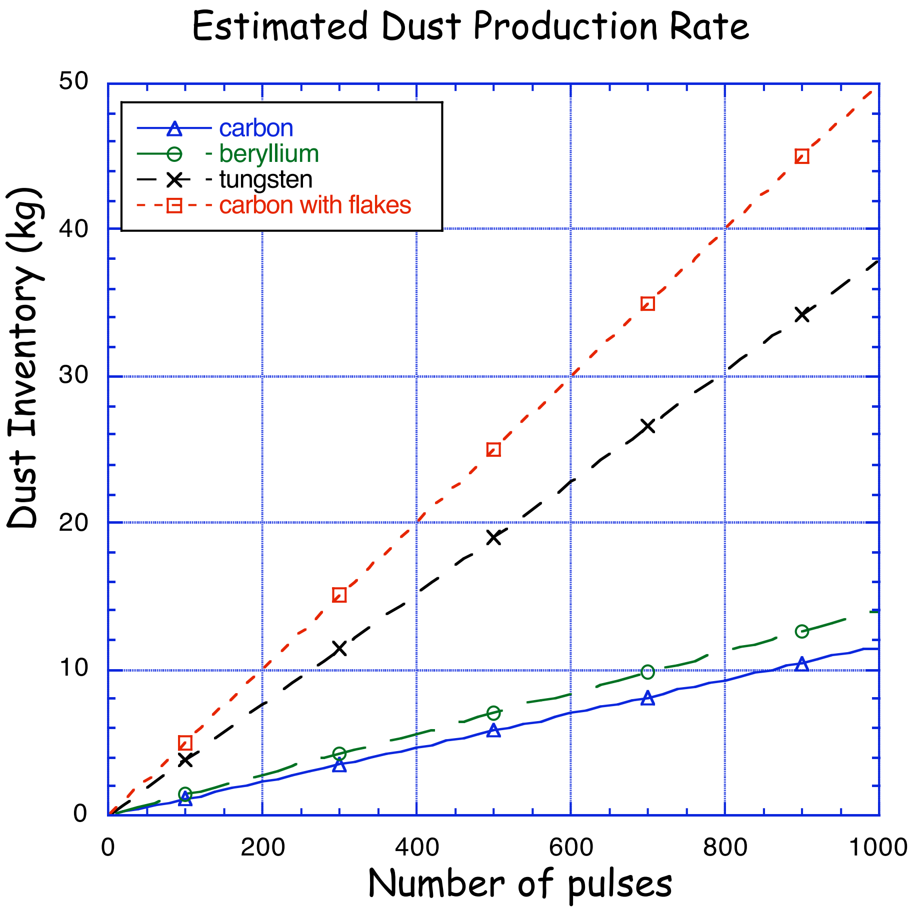
100 nm Ti seed layer, then copper followed by electroplating with 2 μm of Cu.

240 v standoff in absence of dust

Experiment in air

Chris Voinier, NUF fellow

ITER safety depends on limiting dust inventory



ITER schedule calls for 2,000 pulses / year each 400 s duration.
ITER dust production crudely estimated at 10% of sputtered, 50% of evaporated material assumed + flakes for CFC
[G Federici, ITER JCT]

Dust Hazards:

Dust	Safety Issue	Limits (kg)
Beryllium	Reactivity with steam and H_2 Toxic	10-20 on hot surfaces
Carbon	Tritium retention Explosion with air	~100
Tungsten	Activation	100-400

- Limits for C-and Be-dust are related to an explosion (e.g., H produced by Be reactivity with steam from loss of coolant accident).
- The limit for W-dust is related to the containment function of the ITER building (is more flexible).

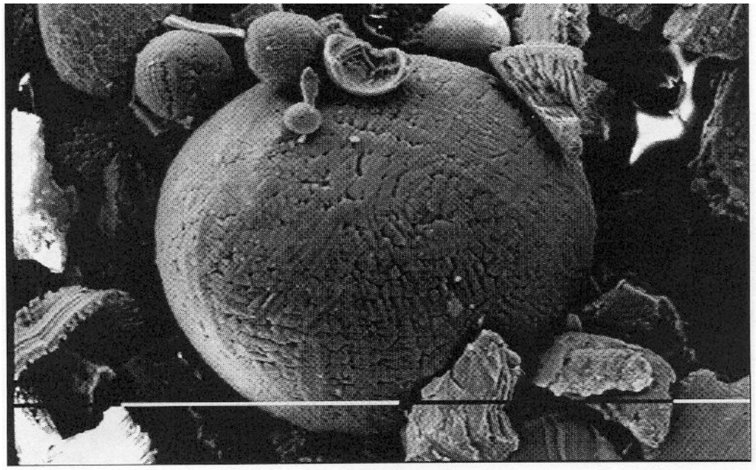
Risks of dust to ITER operations

1. IF regulators are unconvinced that dust inventory is known
   - no authorization of plasma operations until situation fixed (but how?).
2. IF dust measurements are convincing, but inventory is above safety limits
   - operations stop until dust is removed (but how?).
3. IF transport of high-Z dust contaminates plasma core
   - plasma unable to reach Q=10 until dust is controlled (but how ?)

Debris and dust in TFTR and TEXTOR

TFTR vessel floor

1 cm



0.1 mm

Iron spheres from TEXTOR-94 with the large sphere showing a regular surface texture
J Winter, Plasma Phys. Control. Fusion, 40 (1998) 1201

- Risks of Carbon
- Risks of Dust
  - Lab results on novel electrostatic dust detector
  - Risks to ITER operations & goals
- Opportunities for US
  - ITER's PFC dilemma
  - R&D opportunities to mitigate risk

ITER's PFC dilemma:

- Resolving some first wall issues is part of ITER's mission.
- However the technical risks are exacerbated because no contemporary tokamak uses the mix (C/Be/W) of materials or macrobrush components envisioned for ITER.
- ITER has uncomfortable choice for divertor strike plate material:

1. Sticking with carbon (high risk that tritium removal will cripple DT plasma operations.)

2. Sitting on fence (current strategy)
BUT:
H, DD experience will not help much as:

• Retention in hydrogen phase will be obscured by H_2O in tiles.

• Deposition diagnostics NOT part of ITER diagnostic requirements.

• R&D funding dissipated in directions that will inevitably be abandoned.

• Switching from C to W for DT phase entails serious delays to develop new plasma scenarios + potential complications with mixed materials from residual carbon

3. Switching to tungsten (but ITER physics base is mostly from carbon machines.)

R&D opportunities to mitigate risk:

For Carbon:

- ONLY meaningful step is intensive development of promising H-isotope removal techniques with goal of 1-day >90% D removal in current tokamak (DIII_D?) with high performance plasmas next day and funding profile for completion within few years
- PLUS commitment to make changes in ITER design (divertor dome, tile gaps, exhaust processing plant …. to make T removal feasible on ITER).
- PLUS massive R&D program on processing DTO (US responsibility),
- PLUS funding to develop deposition diagnostics….

OR - abandon, carbon specific R&D since it will have NO value for ITER-DT.

For Dust:

- Review ITER dust safety limits
  - present ones date from ITER EDA (US was leader in this).
- Continue investigate dust formation and transport in contemporary tokamaks
  - could this explain JET retention ?
- Solicit and fund proposals to diagnose dust and to remove dust.

Maybe biggest risk that 6 ITER parties will concentrate on their contractual obligations to produce major items of equipment and reduce R&D funding (as in proposed FY2006 budget).

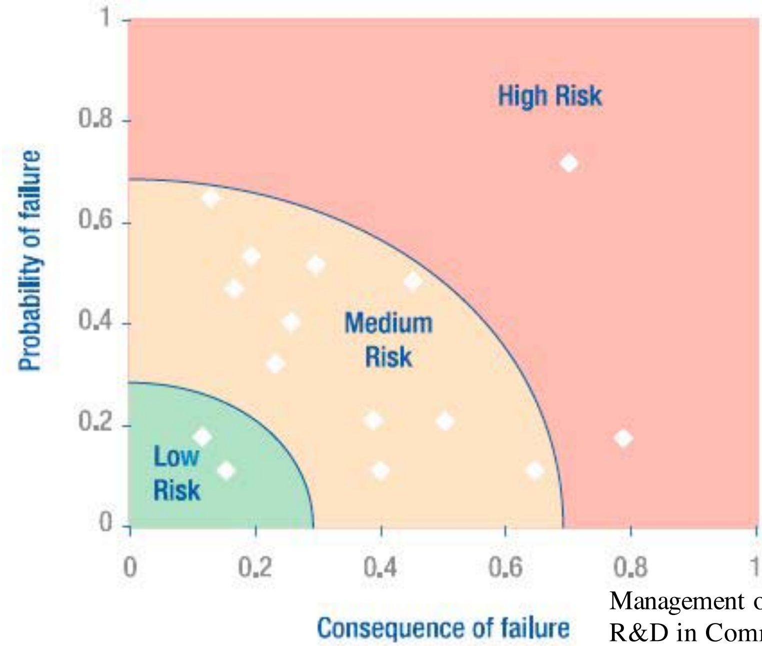
Ownership ?

- We must recognize that these issues have been known for 15+ years but not resolved.
- At present ITER R&D is 'voluntary' however there is no incentive to tackle these thorny orphan areas with uncertain technical impact, with cost & schedule overuns likely.
- The result is unnecessary risk of project failure while needed R&D is neglected and R&D funding in US is diverted to major items of equipment.

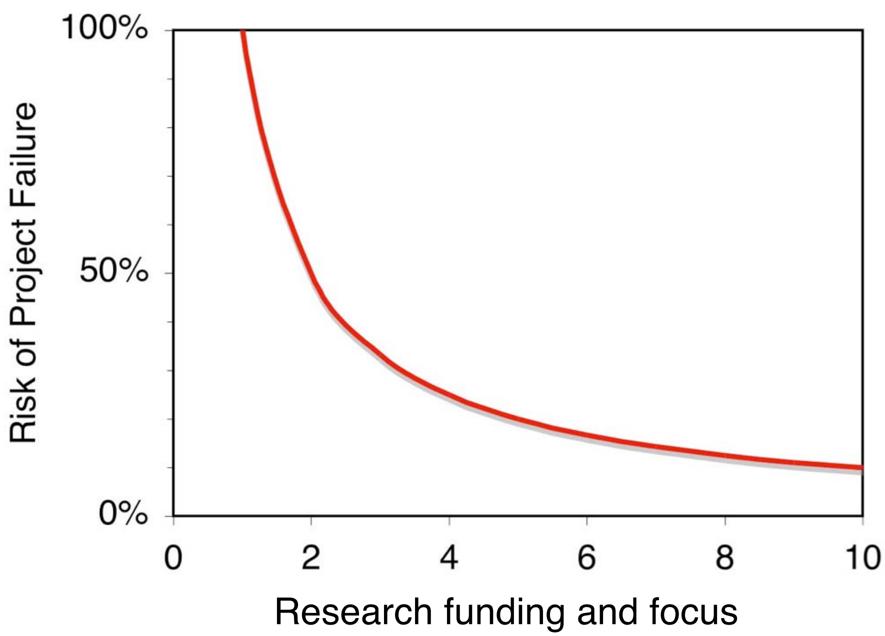
RECOMMEND US support for:

- ITER Technical Review with clear identification of risks and R&D opportunities to mitigate them (in progress).
- Clear alignment of responsibility, authority and funding for 'orphan' issues with proven method to advance solutions - competitive solicitations.
- Central team to solicit and fund best proposals for mitigating high risk / high consequence items, financed by 'tax' from parties.

Project Risk Analysis



Management of Scientific R&D in Commonwealth Agencies



Time is short….

The Arctic perennial ice cover has been decreasing at 9 to 10% per decade.

Polar bears may be extinct by end of 21st century.

Many Carribean reefs have seen a 80 % decline in coral reef cover partly due to global warming

Further info:

- PSI review: Nucl. Fusion 41 (2001)1967; Tritium removal: Physica Scripta T111, 92-97, 2004.
- G. Federici and C. H. Skinner, "Tritium Inventory in the materials of the ITER plasma-facing components" in *Understanding Plasma-Surface Interactions*, Vol. 78, Springer Verlag, Heidelberg, pp. 287-317 (2005).